Figure 10[3] shows the effect of evaporation on the discharge for a relatively short rain. For this figure the values of the constants are as follows: $t_0=15$ hours, $L=300$ miles, $W=40$ miles, $r=0.20$ inch per hour; $E=0.015$ inch per hour; $v=4$ miles per hour; $c=20$ hours; $t=20$ hours and $\varepsilon=0.015$ inch per hour. The values of E and ε are very high. Such high values are purposely assumed so as to form a conclusion of the maximum effect evaporation may have in diminishing the height of the crest. For this same reason W is purposely made large so that the time after the rain stops may be long during which evaporation may take place. The maximum discharge with evaporation neglected is 463.4 mile-inches per hour and 440.1 when corrected for evaporation. This is an extreme case and the effect of evaporation is only about 5 percent. In this case the effect of evaporation on the time of the crest is extremely minute.

Figure 11 was constructed from different values of the

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[3] The figures are numbered consecutively with those in papers I and II.

constants. In this case the values were purposely chosen to show the maximum effect evaporation may have on the time of the crest. For this figure $t_0=45$ hours, $L=180$ miles, $W=40$ miles, $r=0.15$ inch per hour, $E=0.015$ inch per hour, $v=4$ miles per hour; $c=40$ hours. It is further assumed that $\overline{t}>t_0+L/v$. When evaporation is neglected, the time of the crest is 65 hours 38 minutes from the beginning of the rain, and is 64 hours 9 minutes when evaporation is considered.

Figure 12 was constructed to show the effect of evaporation on discharge when there is no surface run-off. Here $c''=0$ and $c'=c=500$ hours, $t_0=60$ hours, $L=240$ miles, $W=200$ miles, $r=0.05$ inches per hour, $\varepsilon=0.005$ inches per hour, $v=4$ miles per hour. The effect of evaporation in this case is small also. Here the width of the drainage area has purposely been chosen 5 times as large as in the two earlier cases because of the scale in the figures.

PRELIMINARY REPORT ON A STUDY OF ATMOSPHERIC CHLORIDES

By WOODROW C. JACOBS

[University of California, Scripps Institution of Oceanography, La Jolla, Calif., August 1936]

An investigation of the salt[1] content of the air was begun at the Scripps Institution in January 1936. The primary purpose of the investigation, at the time it was initiated, was to attempt to prove that the formation of shallow haze or fog (salt haze), peculiar to coastal regions, is due to the presence of comparatively large salt particles or droplets of concentrated sea water suspended in the air. However, a later survey of the available literature in the field of colloid meteorology revealed that such an investigation might serve to fill a gap in our present knowledge of the sources of condensation nuclei. It was felt that a knowledge of the probable sizes of the particles and their effectiveness as condensation nuclei together with a determination of the salt content of the air would make deductions possible regarding the importance of the sea as a source of atmospheric nuclei.

CONDENSATION NUCLEI AND ATMOSPHERIC NUCLEATION

Since the experiments of John Aitken and C. T. R. Wilson, it has been known that condensation of water vapor will not occur at ordinary humidities in air which does not contain colloid particles to act as condensation nuclei. Lord Kelvin (1) explained this as an effect of the increased vapor pressure over a convex surface, which would render condensation impossible in the absence of a nucleus. Later experiments, however, indicate that it is probably a question largely of true metastability. Studies of the nature and effects of these nuclei have been made by numerous investigators, the results of whose researches may be found in many published papers; yet, very little is known concerning the origin of those suspensoids which are active in the atmospheric condensation processes.

Dust particles were at first considered to be the active nuclei; but subsequent investigations by Wigand (2), Boylan (3), Owens (4) and others have proved beyond a doubt that these neutral particles will act only at enormous degrees of supersaturation. Aggregates of the air molecules and complex water molecules may also be eliminated from further consideration on the same grounds. Molecular ions have been considered, but C. T. R. Wilson proved that they were effective only under the extreme

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[1] The term "salt", herein used, is not limited to $NaCl$.

conditions imposed within his cloud chamber. He found that to produce condensation on negative ions a relative humidity of 420 percent is required, on positive ions 790 percent. Appreciable supersaturation is necessary before condensation will take place on even those large, slow-moving, charged particles, the Langevin ions; therefore, it seems as though we may safely disregard these, too, as being effective in an atmosphere where such a state seldom exists. In fact, as stated by Willett (5):

> The whole trend at present, in the light of increasing observational data on the conditions actually prevailing in clouds where condensation is taking place, is to postulate an ever smaller degree of supersaturation in these processes.

It has been observed many times that fogs and clouds frequently form at relative humidities well below 100 percent, which condition seems to be the rule in some localities rather than the exception. On the other hand, even very slight degrees of supersaturation are seldom found in fogs and clouds and then, usually, only under extreme conditions of cooling. That this condition is more frequent at high levels, say in cirrus clouds, or in cumulo nimbus clouds, may be true. Evidence at the present time points to the importance of the hygroscopic aerosol in the condensation process. It is well known that the vapor pressure is lower over a solution or a hygroscopic substance than over a plane water surface, hence, such particles in the atmosphere, coupled with a large curvature, constitute extremely effective nuclei for condensation.

As to the origin of these particles, there is considerable difference of opinion. According to Bennett (6), there are two obvious possibilities—the sea and chimneys. It would be expected that the sea would contribute most of those nuclei effective over and near the sea, while those resulting from combustion are no doubt of extreme importance near such sources of pollution. However, there is no evidence indicating that there has been any great change, except locally, in the balance of nature in this respect since the rise of industrialism. Therefore, Köhler (7), Simpson (8), Melander (9), Ludeling (10) and others believe that the sea is the primary source; a reasonable conclusion when it is considered that five-sevenths of the earth's surface is water. In support of such a theory, Köhler from his analyses of rains, snows, and rime, found an almost constant chloride content even at great distances

from the sea, and also determined the presence of other salts in the same proportion as found in sea water. However, the results given by Riffenberg (11), from a survey of 200 published papers on analyses of rain water, do not indicate that this is true, but that the ratio of chlorides to sulphates, for instance, averages about 3 to 5. In spite of this evidence, nuclei counts made over the sea have invariably been of a small order, while similar counts in rural or urban areas have given comparatively large values. As suggested by Landsberg (12), there must be more chloride present in sea air than is indicated by condensation nuclei counts in such air.

APPARATUS AND METHOD OF ANALYSIS

No detailed description of the apparatus or of the procedure will be attempted here; it is expected that these important details will be fully described and illustrated in a later and more complete report. In brief, however, the method of sampling consisted in passing a measured volume of air, reduced to a temperature of 0° C and a pressure of 760 mm, through a wash tower and filter; these served to remove all of the suspended matter and bring the salts into solution. The wash tower, itself, with a small sintered-glass filter fitted into the bottom (porosity 20 to 30 microns), was partially filled with chloride-free distilled water. After each run, which required from 6 to 12 hours, the liquid was carefully removed from the wash tower and the parts carefully washed. The contents, now about 500 cc, were then evaporated down to roughly 10 cc in order to increase the concentration of Cl. The amount of chloride present was determined by a titration method similar to that described by Riffenberg (13), with some changes due to the fact that such small quantities of the fluid to be analyzed were available. The titrations were made with a silver nitrate ($AgNO_3$) solution, potassium chromate (K_2CrO_4) being used as the indictor, and of such normality that 1 cc of the silver nitrate solution was equivalent to 0.1 mg of Cl. No doubt an electrometric method could have been used with success but it was desired to perfect a procedure which would not limit the analyses to sodium choride determinations.

The apparatus was mounted in the physics laboratory on the third floor of Ritter Hall, about 100 feet above sea level and only 200 feet away from the ocean high-tide mark; all collections were made at this point, the wash tower being mounted outside. During each run a complete record of the various meteorological elements was kept, such as wind speed and direction, pressure, temperature, humidity, total solar radiation, evaporation, visibility, state of the weather and sea, and air mass type. The data presented in table 1 are average values for the period of each collection. The series was made for the most part during May 1936, and consisted of 23 separate analyses. The period was characterized by a general lack of cyclonic activity which was rather unfortunate inasmuch as it was desired to correlate the variations in the chloride content of the air with changes in the various meteorological elements. Qualitative analyses made earlier in the year, under more extreme weather conditions, indicated higher chloride values than are shown by this series.

RESULTS OF THE ANALYSES

The analyses proved that there is considerable chloride present in the air and that the supply is continually being replenished from the sea. It is indicated, further, that a large proportion of the particles must be of such small size that they are capable of remaining suspended in the air.

Except for an excess of chloride, which might occur with the presence of extremely large droplets or sea spray resulting from high on-shore winds, it is believed that the droplets of sea water are true colloidons and, as such, even without evaporation, may be considered as semipermanent in the atmosphere. That is, they may remain suspended permanently unless removed through condensation and precipitation.

As illustrated in table 1, there is considerable variation in the chloride content of the various samples, the maximum content represented by sample number 4, is 0.518 milligrams of chloride per cubic meter of air; the minimum content, represented by sample number 5, is 0.076 mg per cubic meter. The average of the 23 analyses is 0.228 mg. These values would be equivalent to 0.854, 0.125, and 0.376 milligrams of sodium chloride (disregarding the magnesium chloride) per cubic meter of air respectively. As has just been suggested, these values are probably lower than would be found under more extreme weather conditions.

TABLE 1.—*Atmospheric chlorides*

Sample no.	Date	Cl	Wind		Humid-ity	Visi-bility
			Direction	Velocity		
	1936	*mg/m³*		*m/sec.*	*Percent*	
1	Apr. 28	0.247	SW	4.8	66	8
2	May 6	.142	SW	5.6	66	8
3	May 7	.340	NW	4.2	33	8
4	May 8	.518	W	4.1	42	8
5	May 8–9	.076	NW	1.1	51	8
6	May 10	.157	NW	2.6	82	6
7	May 11	.131	NE	2.4	81	6
8	do	.257	W	5.1	69	8
9	May 11–12	.278	SW	2.5	80	7
10	May 12	.267	W	4.0	62	8
11	do	.198	W	2.9	81	7
12	May 13	.102	NE	2.4	79	6
13	do	.250	NW	4.3	55	8
14	do	.186	N	1.9	75	8
15	May 14	.234	NW	3.4	75	8
16	do	.268	NW	6.0	61	9
17	do	.290	NW	2.5	85	8
18	May 15	.122	S	4.0	84	7
19	do	.407	SW	3.9	57	8
20	May 15–16	.146	SE	2.7	81	8
21	May 16	.340	S	5.7	67	7
22	do	.093	S	4.2	78	7
23	May 17	.194	SW	4.0	67	8
Average or mode.		.228	NW	3.7	68.6	8

In attempting to correlate the variation in the chloride content of the air with variations in wind speed and direction, relative humidity, visibility, etc., average conditions for periods of 6 to 12 hours had to be used. This method, in itself, tended to be a smoothing process, throwing most of the observations into several large divisions of each meteorological element and leaving only a few cases to represent the extreme conditions. Therefore, all elements illustrated in the several figures have been divided into a few large groups. In all cases, too much stress should not be placed on the extremes.

The most outstanding relationship is that of chloride content to wind velocity; as illustrated in figure 1, the chlorinity appears to vary directly as the wind velocity. There is also considerable variation in the amount of chloride with different wind directions; winds from the sea, of course, present the higher values. These data are represented graphically in figure 2.

A fair correlation between the chlorinity and relative humidity was found. The curve in figure 3 shows a decreasing chloride content with increase in humidity. This result seems reasonable when it is considered that a great many of the particles must be effective condensation nuclei, and as a result probably become nuclei of water

droplets at less than saturation values and thus settle out.

Many counts of condensation nuclei (cf. Landsberg, loc. cit.), have indicated a decrease in visibility with an increase in impurities; but an examination of figure 4 shows the opposite condition to be true here. Apparently these colloidons are not effective scattering agents.
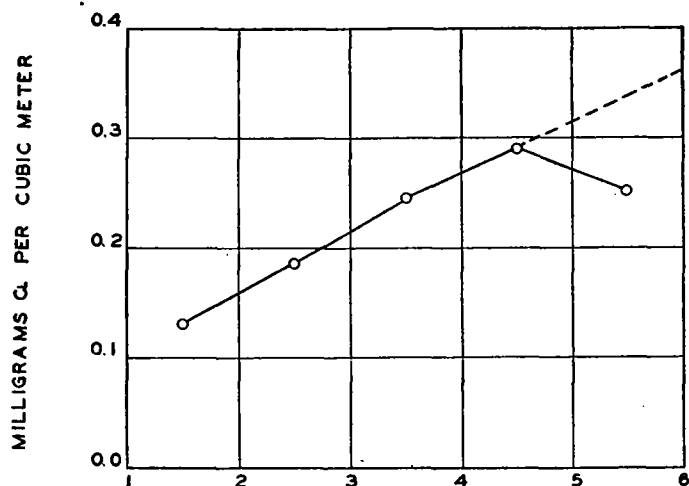

FIG. I   WIND VELOCITY (M./SEC)

There appears to be considerable variation in the chloride content of the various air masses; but it would be expected that local influences at this seacoast location would tend to obliterate any actual variation that might
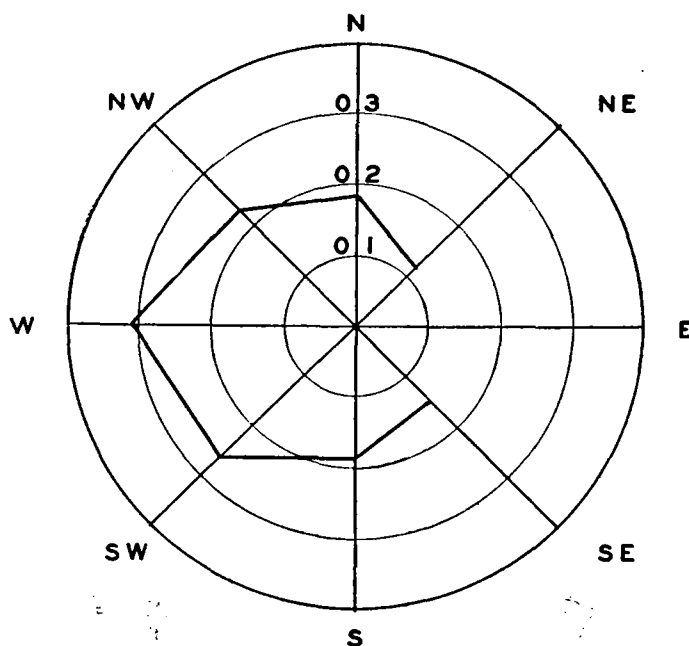

FIG. 2   WIND DIRECTION

exist unless a long series of observations were available. The present series is too short to determine much more than that maritime air masses, both fresh and transitional types, present higher chloride values than do those of continental origin. Ts (superior) air masses, in particular, presented low values, which agrees with the results of counts of condensation nuclei in air masses of high-level origin.

THEORETICAL CONSIDERATION OF THE DATA

When one considers that the ocean surface is constantly agitated by wind and waves, it is only logical to assume that much ocean water in the form of spray is temporarily suspended in the atmosphere. The surface tension of the small droplets causes them to evaporate and leave their salt content as suspensoids in the air. It is interesting
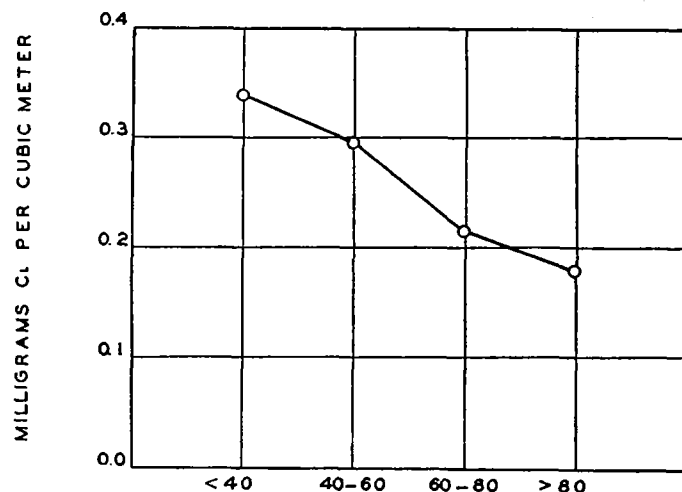

FIG. 3   RELATIVE HUMIDITY (%)

to consider that 0.1 mg of Cl, as collected, represents the chloride content of slightly more than 5 mg of sea water at normal chlorinity; or, more correctly, 0.1 mg of sea salt represents 2.86 mg of sea water at normal salinity. In other words, there would be a loss of nearly 30 times by weight before a salt crystal would be left. However, it is not suggested that these colloidons consist of minute
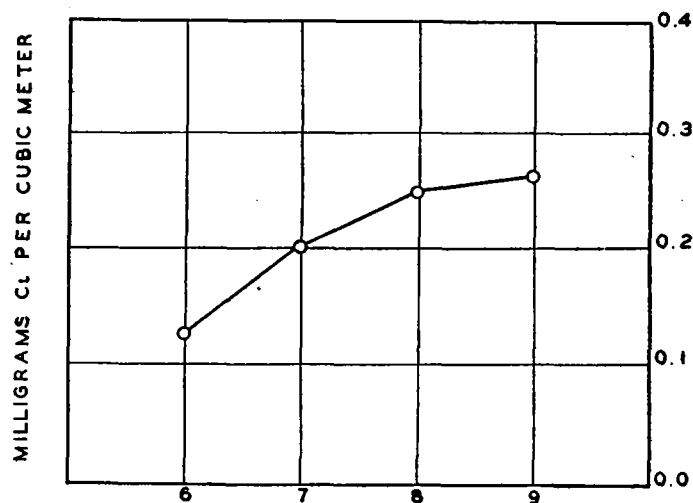

FIG. 4   VISIBILITY

crystals of sodium and magnesium chloride; in all probability they are most frequently small droplets of concentrated sea water. In any event, there is no reason to suppose that any one nucleus would be more highly hygroscopic than any other, for it would be expected that each would contain all of the salts found in sea water and in the same ratios. (See table 2.) Thus these nuclei would be more hygroscopic than pure NaCl because of the presence of $MgCl_2$, $MgSO_4$, and smaller quantities of

other highly soluble substances. Since the ocean surface of the earth far exceeds the land surface and the process of adding salt particles is a continuous one, it is not unreasonable that Köhler should find the ratios between the various salts of the ocean and precipitation similar.

Hess (14), in his counts of condensation nuclei, found an average of 1,060 nuclei per cubic centimeter of air over the North Sea and 800 over the Atlantic Ocean. Krocke found 1,130 per cc over the South Atlantic; while Davis, in the Pacific, found the number to range from 2,000 to 5,000. Landsberg (12) reports an average of 950 particles over the Atlantic Ocean, but he does not believe that this relatively small number accounts for all of the NaCl found in precipitation. It is his opinion, however, that combustion products contribute only slightly to the hygroscopic salt content of the air (15). As stated by Bollay and Kraght (loc. cit.):

The significant result of these data is that there is found an almost constant (neglecting Davis' findings) distribution of hygroscopic salt particles over all ocean surfaces. In view of the much smaller land surfaces of the earth and the continual advecting and mixing process in the atmosphere, it is only logical to assume that also everywhere over land the number of suspended salt particles is of the same order.

TABLE 2.—Salt content of sea and precipitation

Salt	P. p. thsd. of sea water	Percent of total	P. p. m. of precipitation (Köhler)	Percent of total
NaCl	27.213	77.758	5.03	77.50
MgCl₂	3.807	10.875	.70	10.79
MgSO₄	1.658	4.737	.47	7.24
CaSO₄	1.260	3.600	.29	4.47
K₂SO₄	.863	2.465		
CaCO₃	.123	.345		
MgBr₂	.076	.217		
Total	35.000	99.997	6.49	100.00

Köhler has computed that the average condensation nucleus is of the order of size of 0.1 micron and has a mass of 10^{-15} grams. Taking the chloride results of this investigation, and assuming it all to be bound with sodium, the average NaCl content would be equivalent to 376,000 such particles per cubic centimeter of air. Even the minimum sodium chloride content, represented by sample 5, would be equivalent to 125,000 nuclei. The maximum value, represented by sample no. 4, would give nearly 1 million of these Köhler particles per cubic centimeter of air. Obviously, either these nuclei are larger than has been assumed by Köhler or they occur in far greater abundance than is indicated by nuclei counts made over the sea by various investigators. It is suggested that both are probably true.

Let us consider first the validity of the nuclei counts. It has been shown that the average is about 1,000 per cubic centimeter of sea air. C. T. R. Wilson (16) found that if the air admitted to the nuclei counter is expanded slowly, fewer drops are formed, than if the operation is rapid. This is due to the fact that as soon as cooling begins, condensation starts on some of the nuclei, with the result that some vapor is removed from the atmosphere and the final supersaturation is less than it would otherwise be. Bennett (6) concludes, therefore:

" * * * that all nuclei counted in the Aitken counter are not necessarily effective as condensation nuclei in the atmosphere, or, more correctly, some are far more effective than others."

A nuclei counter of the Aitken, or similar, type was not available for the study of this problem. However, at first

analysis, without consideration of the mechanical details of the counter, it seems as though it would be just as possible to present Bennett's statement in the opposite fashion, e. g., the values given by the Aitken counter do not necessarily include all of the condensation nuclei effective in the atmosphere. Some particles may be so much more effective than others that they will become nuclei of large water droplets at low saturation values and grow at the expense of smaller, but effective, particles. Thus the removal of these large nuclei by condensation and precipitation might actually give higher nuclei counts than would be recorded if they were still present. This reasoning, then, would account for the low nuclei values recorded over the sea.

Köhler has assumed that by some selective process, salt particles or droplets of one particular size are driven from the sea. However, it seems that whenever a wave of the sea breaks on the shore, whenever a wavelet overturns, whenever a bubble in foam breaks up into fine droplets when the bubble bursts, as in the formation of mists during effervescence,[2] aerosols are produced by the mechanical dispersion of the liquid. Thus we would not expect the droplets of sea water produced to be of uniform size but to vary from that of the smallest liquid drop possible to those of such large size that they immediately fall back into the sea. That there would be a tendency, under a given set of conditions, to produce a large proportion of droplets which approach some given size is no doubt true.

Next we might consider the validity of Köhler's assumption as to the size of nuclei. When it is considered that it would take only 2.86×10^{-14} grams of sea water to produce a salt particle of the size assumed by Köhler, it is obvious that there is a great possibility for much larger particles to become suspended in the air and still be of true colloidal dimensions. H. G. Houghton (18), in a recent study, found that the sizes of droplets in sea fogs distributed themselves according to a frequency curve with a single and very pronounced maximum, with a slight positive skewness and asymptotic to the axis for large particle sizes. He suggests that the upper portion of the curves would represent the distribution of nuclei sizes greater than a certain minimum size. He believes, further, that the nuclei were NaCl formed by the evaporation of sea spray and assumed a random distribution of sizes. The absence of secondary maxima would indicate that there had been no appreciable combination of the drops. Inasmuch as all nuclei would be expected to be equally hygroscopic, the sizes of the fog droplets would be solely a function of original nuclei size, discounting the effect of a possible electric charge.[3]

CONCLUSION

It is expected that additional chloride determinations will be made under a greater variety of meteorological conditions and in various locations, some at high altitudes above inversion layers and at distances inland. There is, in addition, little reason to limit the study to chlorides. The establishment of ratios between the various salts present will allow further conclusions to be drawn concerning the importance of combustion and dust in atmospheric nucleation; and the accumulation of more data will allow many further problems to be considered at length.

As a final statement, the writer wishes to gratefully acknowledge the constant assistance and advice of Dr. R. H. Fleming of the Scripps Institution, without whose aid this study would never have been undertaken. He

[2] It has been shown by Stuhlman (17) that the number and size of the droplets is largely a function of bubble size.
[3] It has been shown, experimentally, that the charges on nuclei seldom exceed one electronic charge. A charge of plus or minus many times this number of electrons would be of infinitesimal importance in rendering the nucleus more hygroscopic.

wishes, further, to acknowledge the kindly interest and helpful suggestions of Dr. Geo. F. McEwen, S. W. Chambers, and Drs. D. L. Fox and C. E. Zobell, also of the Scripps Institution.

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DUSTSTORMS OF JANUARY–APRIL 1937 IN THE UNITED STATES

By R. J. MARTIN

Precipitation for the first 3 months covered by this summary averaged above normal in all but five States, in four of which rather severe duststorms occurred during the period. January, with the greatest percentages of normal precipitation in the Plains States and most of the Dust Bowl, had the fewest duststorms, while March, with substantial to heavy precipitation in the Plains States, and much less than normal in most eastern sections, had the most extensive storms. April brought above-normal precipitation to the far Northwest, portions of the northern Great Plains, the middle and upper Mississippi Valleys, and, except for Arkansas, Louisiana, Mississippi, and Tennessee, to all States east of the ninety-fifth meridian.

During January, widespread dusty conditions prevailed over a large central area, reaching from Illinois westward to eastern Wyoming. These duststorms, mostly light, were scattered throughout the month, but were most numerous during the latter half; dense dust was reported in portions of New Mexico, Oklahoma, Texas, Colorado, and one or two other Southwestern States. Colorado had an unusual number of violent duststorms during the month in southeastern counties, where soil blew badly with only light to moderate wind movement; in Baca and Prowers Counties the storms were severe on the 5th, 13th, 15th, 17th, 23d, 27th, and 31st, with an average duration of 6 hours, and average visibility of from three city blocks to one-half mile. Considerable soil erosion occurred in New Mexico during January, and by the end of the month the soil was beginning to blow in southwestern Kansas.

The storms of February were more numerous and severe than those of January, and were reported over a wider area. Dusty conditions were noted from Brownsville, Tex., northward to the Canadian border, and from New Mexico, Colorado, and central Montana eastward to the Lake region and the Ohio Valley; aviators encountered dust clouds at elevations of 12,000 feet. Observations and computations made by Soil Conservation officials indicated that in one storm, Page County, Iowa, received 274 pounds of dust per acre, while at Sault Ste. Marie, Mich., the fall amounted to 11.65 tons per square mile; Drs. Hunt and Halverson, Northern State Teachers College, estimated the fall at Marquette, Mich., at 14.9 tons to the square mile.

The following extracts are from a letter written by A. E. Osborn, official in charge at the Dodge City, Kans.,

Weather Bureau office, describing a trip through a portion of the Dust Bowl:

* * * Light dust was blowing with a southwest wind when we left Dodge City, with visibility a little over a mile. Light dust continued until we were about 10 miles north of Liberal (Kans.) where a dense dust cloud blew in from the north and brought visibility down to 15 or 20 feet at once. The driver experienced great difficulty in staying on the road. After an hour or more of this almost blind driving we arrived at Liberal at 7:10 a. m. We left Liberal for Hooker, Okla., at 7:20 a. m. The dust continued very thick and frequent stops were made because the visibility was practically zero. Three hours and forty-five minutes were required to drive the 23 miles. * * * The trip from Liberal, Kans., to Dalhart, Tex., was through part of the very worst section of the Dust Bowl. * * * Through this region there was very little evidence of any moisture in the soil. The topsoil was very dry and powdery and there was practically no moisture * * * for a depth of several feet. Finely powdered dust was in evidence everywhere, in drifts several feet high, depending upon the height of the object causing the drift. Deserted farm homes seemed to be the rule rather than the exception * * * (Feb. 17, 1937).

Severe soil erosion occurred in some southeastern districts of Colorado during this month, and most wheat, and even buffalo grass, suffered. On the 5th visibility was reduced to 100 feet in Baca County, and at Pueblo dense dust prevailed on the 7th for more than 2 hours; zero visibility, lasting from 7 to 10 hours, was reported south of the Arkansas-Platte Divide and east of the mountains. Air and highway traffic was disrupted from 7 to 20 hours per day on the 14–17th, and on the 15th dust was general from Wyoming to the New Mexico border. Kansas had vigorous storms until about the 20th, when several inches of snow fell. Wheat in the western third of Kansas suffered considerable damage. Some stations in Oklahoma reported light to heavy dust on 20 days during the month, and many fields in New Mexico were left ashy, dry, and powdery.

March and April brought the most extensive duststorms that have prevailed in recent months. In March light dust was reported, at the surface or aloft, from the Rocky Mountains eastward to the Atlantic coast, and from extreme southern Texas northward into Canada. Dense dust, however, occurred over nearly the same areas as in the preceding 2 months—portions of the northern and southern Great Plains, southward to Texas, and in the far Southwest.

The most severe storms of March occurred in Kansas, Oklahoma, Texas, New Mexico, and Colorado during the third week, and it was during and after this period that the Middle Atlantic and east Gulf States reported dust.